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16. ABSTRACT

A fluid modeling study was performed in the EPA Fluid Modeling Facility's stratified towing tank to determine the effects of stratification on the flow field over a three-dimensional hill. Streamlines in the stratified flow over an axisymmetric hill were marked with a dye tracer and photographed with a two-camera system. A stereographic technique was developed to analyze the photographic data. The trajectories on the photographs were digitized and processed by computer to determine the amount of deflection of the streamlines as they pass around the hill and the closest approach of each to the hill surface. A range of approach flow Froude number from 1.0 to 8.0 based on the hill height and neutral flow were modeled.

The vertical and lateral deflections of the streamlines as they pass around the axisymmetric hill of this study were found to approach the limits for neutral flow at a Froude number of about 6.0. For Froude numbers between 1.0 and 4.0 the deflections were significantly different than those for neutral flow.

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1. INTRODUCTION

In attempting to predict the maximum ground-level concentration from a source upwind of a hill, the most important feature of the flow is the displacement of the mean streamline through the source, because that displacement determines how near to the surface the centerline of the plume will reach. The exact path taken by the plume in circumventing the hill and the plume's closeness of approach to the hill surface are critical in determining the location and magnitude of the ground-level concentrations. These displacements are known to be strongly affected by the hill shape and by the stratification of the approach flow (Hunt et al, 1979; Hunt and Snyder, 1980; Snyder and Hunt, 1984; Snyder et al, 1985).

The purpose of the work described herein was to characterize the effects of stability on the horizontal and vertical deflections of streamlines around an isolated hill. Of particular interest was how large the Froude number must be before the flow becomes essentially neutral. A set of streamline trajectories over an axisymmetric hill was measured using the stratified towing tank of the EPA Fluid Modeling Facility. Three-dimensional coordinates of the streamlines were determined through stereographic analysis of photographs of streaklines of dye released at selected source positions, and at stabilities ranging from moderately stable to neutral (Froude numbers of 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, and infinity). The general features of these measurements are presented, but the data set should prove useful for testing mathematical models and algorithms for describing the detailed structure of stratified flow over hills.

This work is a natural continuation of a similar study by Snyder, et al (1986), which concentrated on the more stable cases.

2. APPARATUS AND TECHNIQUES

2.1 The Towing Tank

The EPA towing tank has a 1.2 m by 2.4 m by 25 m test section. The walls are made of clear acrylic plastic, providing maximum visual access. The model hill was mounted on a flat, square baseplate. This apparatus was turned upside down and suspended from a towing carriage so that the baseplate was submerged approximately 6 mm below the water surface. The apparatus was then towed the length of the tank. Further details of the towing tank and its application may be obtained from Thompson and Snyder (1976).

The coordinate system originates at the hill base center. The longitudinal coordinate, x, increases downstream; y was measured from the hill centerline, positive toward the camera; and z was taken to be positive downward from the baseplate level. Since the model was towed upside down in the tank, the depth z was directly interpreted as height in the atmosphere.

Mixing and distribution systems permit the tank to be filled with any desired shape of density profile. In these experiments, two different profiles were used. For the most stable cases, the tank was initially filled with fresh water at the surface and saturated salt water at the bottom with a linear gradient of density. The density profile tended to erode toward neutral at the surface and bottom of the tank because of the towing operations. Between tows, the neutral layer near the surface was "skimmed" off and the original level was restored by introducing an additional layer of saturated brine at the bottom of the tank. The situation was similar for the weaker density gradient with a specific gravity at the bottom of 1.013.

The tracer used in these experiments was a blue food dye diluted with sufficient salt water to produce an effluent that was neutrally buoyant at the release height. This mixture was released nearly isokinetically from a thin, bent-over tube (1.5 mm ID) located near the upstream edge of the baseplate (x = -7.5H, where H is the hill height).

2.2 The Model

The model used in this study was an idealized representation of Cinder Cone Butte in Idaho. The axisymmetric model shape is given by

$$h(r) = \{(H + c)/[1 + (r/L)^4]\} - c$$

with H = 15.5 cm, L = 38.8 cm, and c = 1.0 cm.

As shown in the figures, the model had a fairly flat top and a maximum slope of 0.45 or 24.4°. The model was mounted on the towing-tank baseplate such that the hill blended smoothly into the flat surface at a radius of 5H.

The density profile measured before each tow was used to set the tow speed U to obtain the desired Froude number

$$Fr = U/(gH\Delta\rho/\rho)^{1/2},$$

where $\Delta\rho$ is the density difference between the base and top of the model hill and g is the gravitational acceleration. The density profile was also used to specify how the refractive index varied with depth.

2.3 Photographic Technique

A photographic technique was developed to measure the three-dimensional plume trajectories (streaklines). Basically, the technique is an application of the common stereographic process in which two simultaneous photographs taken from different vantage points are combined to provide a three-dimensional representation.

Both side- and bottom-view cameras moved with the model as it was towed so that several photos were obtained during each tow. The cameras were fired simultaneously by radio command.

2.4 Photographic Analysis

In the analysis of the photographs, the camera was treated as a point emitter/receptor of light rays which were traced through the walls of the tank and the layers of salt water. Together, the virtual camera and a point in the photograph determine a light ray which can be projected into the tank to recover the actual location of the feature in question. The virtual locations of the cameras, considering the refraction of light through the various interfaces and density gradient of the salt water, were determined by photographing carefully positioned reference grids and using a predictor-corrector method to obtain a least-squares fit for the locations.

Generally, six pairs of photographs were taken during each tow. Of these, three pairs were selected for analysis. The centerline of each plume was estimated by eye, marked on each photograph, and digitized for computer analysis and averaging.

Given the virtual camera positions, the density profile in the tank, and the digitized trajectories from the side- and bottom-view photographs, the three-dimensional trajectories were computed.

All measurements were then normalized by the hill height, H. The maximum vertical and lateral deflections for each case were determined. The plume's closest approach to the hill surface, z_{min}, was also estimated. The resolution of the technique was determined to be on the order of 0.02H.

3. RESULTS

Sixty streamline trajectories were observed and quantified during this study. A total of eight source locations were used: six at various heights on the centerline and two laterally offset sources. Selected parameters determined from related groups of cases will be presented.

Sideview photographs of two experiments with sources on the centerline are shown in Figures 1 and 2 (Fr = 2.0 and ∞, respectively). Three source heights are shown(z_s = 0.5H, 1.0H and 1.5H). All plumes released on the centerline followed a straight path over the hill with no discernible lateral deflection. By comparing the distance above the surface of the streaklines originating at the same height, the magnitude of the effects of stability on the vertical deflection of the flow can be seen. Note that in the neutral case, the turbulence from the source doesn't decay as quickly resulting in a greater spreading of the dye. The streaklines of the Fr = 2.0 case are drawn down near the surface in the lee of the hill.

Figure 3 shows the bottom (i.e. from below the inverted model in the tank) view of the laterally offset sources for Fr = 2.0. The lateral deflections of the streaklines in this moderately stable case are significantly greater than for the neutral flow case.

Trajectories that were produced through the stereographic process as described above are shown in Figures 4 and 5. Figure 4 shows side views of the trajectories from a source at (y_s,z_s) = (0,0.5H) for all Froude numbers modeled. Figure 5 is a top view of the trajectories for a source at (y_s,z_s) = (2.0H,0.5H), also for all Froude numbers. Both the vertical and lateral deflections can be seen to closely approach the values for neutral flow as the Froude number reaches about 6.0.

Selected results for the centerline releases are summarized in Table 1. Results for the offset sources are presented in Table 2. By comparing the parameters for a given source location for various Froude numbers, it can be seen that the trajectories for Froude numbers greater than about 6 are very close to those for the neutral case (Fr = ∞).

4. SUMMARY

The stereographic technique for obtaining trajectories of streamlines in stratified towing tank experiments has proved to be a useful tool for obtaining data on stable flows. The trajectories obtained in this effort should be useful for comparison with theoretical and numerical modeling descriptions of stable flow over three-dimensional obstacles.

The vertical and lateral deflections of the streamlines as they pass around the axisymmetric hill of this study were found to approach the limits for neutral flow at a Froude number of about 6.0. For Froude numbers between 1.0 and 4.0, the deflections were significantly different than for neutral flow.

Much attention in the past has been focused on flow patterns around three-dimensional hills under strong stratification, Fr < 1.0. A dividing-streamline concept (Snyder, et al, 1985) has been established as a working tool for separating the flow into two layers. Below the dividing-streamline the flow deflections are constrained to horizontal planes. The flow above this level is moderately stable (Fr = 1.0 based on the height of the hill above the dividing streamline). Since flow patterns do not approach those for neutral until the Froude number reaches about Fr = 6.0., modeling this upper layer must include stability effects for proper streamline calculations.